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STUDYING RE-SCATTERING EFFECT IN HEAVY-ION COLLISION THROUGH K^* PRODUCTION

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We have studied the K^* production within A Multi-Phase Transport model (AMPT) for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV to understand the hadronic re-scattering effect on the measured yields of the resonance. The hadronic re-scattering of the K^* decay daughter particles (π and K) will alter their momentum distribution thereby making it difficult to reconstruct the K^* signal through the invariant mass method. An increased hadronic re-scattering effect thus leads to a decrease in the reconstructed yield of K^* in heavy-ion collisions. Through this simulation study we argue that a decrease in K^*/K ratio with increase in collision centrality necessarily reflects the hadronic re-scattering effect. Since the re-scattering occurs in the hadronic phase and K^* has a lifetime of 4 fm/c, we present a toy model based discussion on using measured K^*/K to put a lower limit on the hadronic phase lifetime in high energy nuclear collisions.

Keywords: Resonances; Re-scattering; Heavy-ion collisions.

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1. Introduction

High energy heavy-ion collisions form a system whose constituents undertake various type of interactions during different times of evolution of the system. Many resonances have been observed in these collisions¹⁻⁵ - $f_2(1270)$, $\rho(770)^0$, $\Delta(1232)^{++}$, $f_0(980)$, $K^*(892)^{0\pm}$, $\Sigma(1385)$, $\Lambda(1520)$ and $\phi(1020)$ with life times of 1.1 fm/c, 1.3 fm/c, 1.6 fm/c, 2.6 fm/c, 4 fm/c, 5.5 fm/c, 12.6 fm/c and 44 fm/c, respectively. Resonances are very good probes of the dynamics of the system formed

in heavy ion collisions⁶ as they cover from the very early time scales to close to the freeze-out of the system.

In the hadronic phase of the system formed in heavy-ion collisions, two important temperature or time scales comes into picture. One is the chemical freeze-out, where the inelastic collision among the constituents are expected to cease and the other is the later kinetic freeze-out when the distance scales among the constituents are larger than the mean free path due to which all (elastic) interactions cease.^{7–9} If resonances decay before kinetic freeze-out then they will be subject to hadronic re-scattering of the daughter particles which will alter their momentum distributions. This would lead to loss in the reconstruction of the parent resonance. The amount of loss could depend on the life time of hadronic phase (specifically the time between chemical and kinetic freeze-out), resonance daughter particle hadronic interaction cross section, particle density in the medium and the resonance phase space distributions. On the other hand after chemical freeze-out pseudo-elastic interactions could regenerate resonances in the medium leading to enhancement in their yields. For example interactions like $\pi K \rightarrow K^{*0} \rightarrow \pi K$ could happen until kinetic freeze-out. Transport based model calculations indeed predict that both re-scattering and re-generation processes affect final resonance yields.¹⁰ On the other hand thermal model calculations only after including re-scattering effects are able to explain the experimentally measured ratios of resonance yield to the yield of stable particles.^{11,12}

In this work we use A Multi Phase Transport Model (AMPT)^{13,14} to study the effect of re-scattering on K^* resonance production. The K^* in this study denotes the sum of $K^{*\pm}$, K^{*0} and \bar{K}^{*0} . We have modified the AMPT code to track the production of K^* (decayed and newly produced as a function of hadronic cascade time, τ_{HC}) and the change in the momentum distributions of its daughters (π and K). We demonstrate by gradually increasing τ_{HC} , that allows for increased re-scattering effect, the invariant mass signal of K^* reconstructed from the daughter particles (πK) decreases. We present the change in the experimentally measured K^* yield per unit rapidity dN/dy with the increase in τ_{HC} . We propose an experimental observable the ratio of yield of K^* to yield of charged K to understand the re-scattering effect in heavy-ion collisions. Finally using the measured K^*/K ratio, within the framework of a simple model, we obtain the lower limit on the time difference (Δt) between chemical and kinetic freeze-out in high energy heavy-ion collisions.

The paper is organised as follows: in next section we briefly discuss the AMPT model, in section III we discuss the results related to re-scattering effects on the yield of K^* , it also includes a discussion on the model dependent extraction of lower limit on time scale between chemical and kinetic freeze-out and section IV summarises our findings.

2. AMPT Model

The AMPT model^{13, 14} uses the same initial conditions as in HIJING.¹⁵ However the minijet partons are made to undergo scattering before they are allowed to fragment into hadrons. The AMPT model has two versions, one is the default version, the other is called the string melting version. All the results presented in this paper are based on the default version (version 1.25t9b). The hadronic matter interaction is described by a hadronic cascade, which is based on A Relativistic Transport (ART) model.¹⁶ The termination time of the hadronic cascade is varied in this paper from 0.6 fm/c to 30 fm/c to study the effect of the hadronic re-scattering on the observables presented. More detailed discussions regarding the AMPT model can be found in Ref.^{13, 14} In this study, approximately 50000 events for each configuration (different hadronic cascade time) were generated for Au+Au 0-80% minimum bias collisions at $\sqrt{s_{NN}} = 200$ GeV. All results presented are for the rapidity range $|y| < 0.5$.

K^* resonances, together with their anti-particles, are included explicitly¹⁰ in the hadronic cascade of the AMPT model. Both elastic and inelastic hadronic interactions involving K^* are included¹⁴, such as K^* productions, absorptions and decays. In particular, elastic scatterings of K^* with a meson among (ρ, ω, η) are included using a 10 mb cross section, the same cross section as used for kaon elastic scatterings.¹⁶ In addition to initial productions from the Lund string fragmentation, the K^* resonance can be produced from kaon-pion scatterings, while K^* decay is the inverse reaction. They can also be produced or destroyed from reactions such as $(\pi\eta)(\rho\omega) \leftrightarrow K^*\bar{K}$ or \bar{K}^*K , $\pi K \leftrightarrow K^*(\rho\omega)$,¹⁷ $\phi(\pi\rho\omega) \leftrightarrow (KK^*)(\bar{K}\bar{K}^*)$, and $\phi(KK^*) \leftrightarrow (\pi\rho\omega)(KK^*)$.¹⁸

3. Results

3.1. Invariant mass distribution

Figure 1 shows the time evolution of K^* yields for minimum bias Au+Au at collisions $\sqrt{s_{NN}}=200$ GeV from the default version of AMPT. Red solid triangles represent the total number of K^* present at a given time in the hadron cascade. Open blue circles represent the total number of produced K^* , black crosses represent the total number of decayed K^* , while their difference corresponds to the total number of K^* present at the time. We see that the number of K^* present reaches a peak after several fm/c (partly due to the finite formation time of hadrons) and then slowly decreases with time; it will eventually vanish at large enough time as the system expands and resonances decay away.

The πK daughters of the K^* decayed will undertake re-scattering effects which is expected to increase with increase in τ_{HC} . The hadronic re-scattering of daughter πK would then lead to loss in K^* invariant mass signal. The regeneration of K^* though will also pick up with increase in hadron cascade time, however if not dominant will not be sufficient to compensate the loss due to re-scattering. The K^*

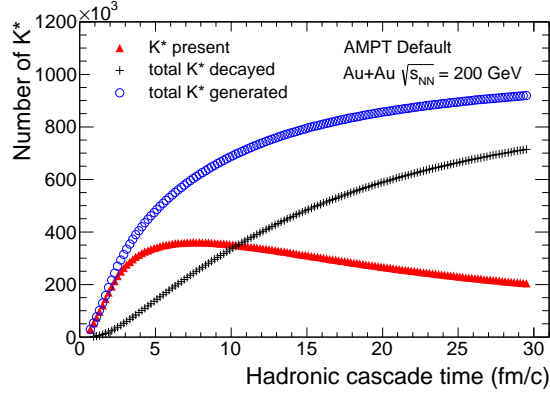
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Fig. 1. (Color online) Number of K^* as a function of hadron cascade time in the default version of the AMPT model for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Red solid triangle corresponds to total K^* present at any given hadron cascade time. Blue open circle corresponds to total K^* produced. Black cross corresponds to total K^* decayed.

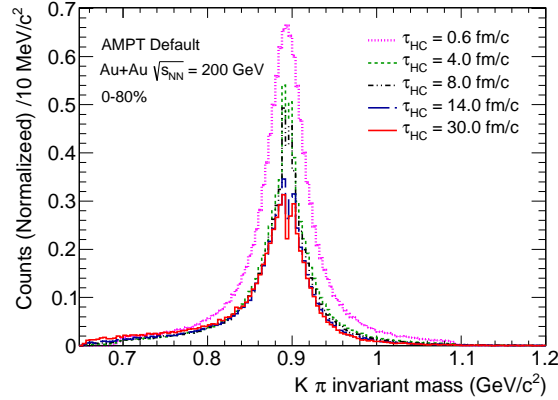


Fig. 2. (Color online) $K^* \rightarrow \pi K$ invariant mass distribution in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the AMPT model. The different distributions correspond to different termination time of hadron cascade (τ_{HC}). The number of events are kept the same for all the configurations.

regeneration depends on the the cross section $\sigma_{K\pi}$ while the re-scattering of daughter particles depends on cross sections $\sigma_{\pi\pi}$ and $\sigma_{K\pi}$, where $\sigma_{\pi\pi}$ are considerably larger (factor ~ 5) than $\sigma_{K\pi}$.^{19–21}

Figure 2 shows the invariant mass of K^* meson reconstructed using four momentum information of the π and K in minimum bias (0-80% of the total cross section) Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The results are shown for different config-

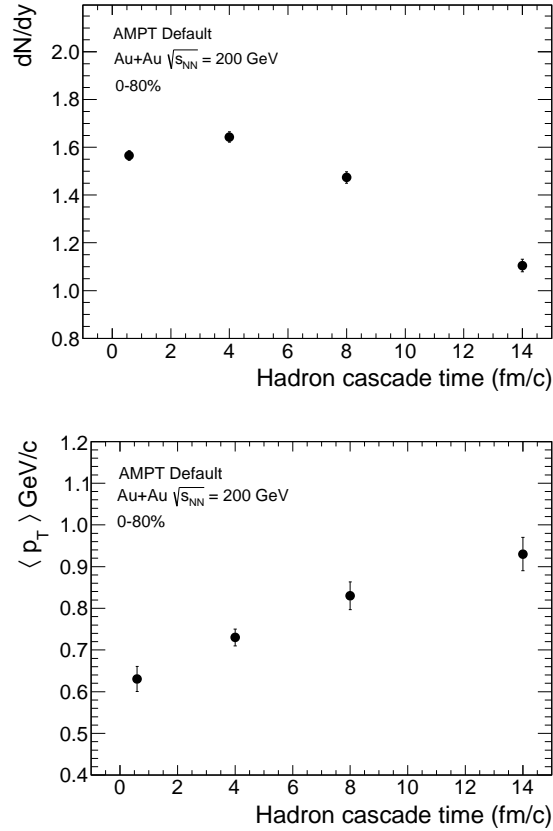


Fig. 3. dN/dy (upper panel) and $\langle p_T \rangle$ (lower panel) of K^* meson in AMPT model for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV as a function of hadron cascade time.

urations of AMPT calculations where the termination time of the hadron cascade is varied from 0.6 to 30 fm/c. The number of events generated for each configurations are kept the same in order to make proper comparisons. Clearly one observes a decrease in the invariant mass signal as the hadron cascade time increases. An increase in hadron cascade time corresponds to increase in hadronic re-scattering effects in the AMPT model. The loss in K^* signal strength is anticipated due to the change in momentum of the daughter π and K of K^* meson as a result of hadronic re-scattering. However we have observed that the reconstructed K^* mass and width are not affected by the hadronic re-scattering process as implemented in the model.

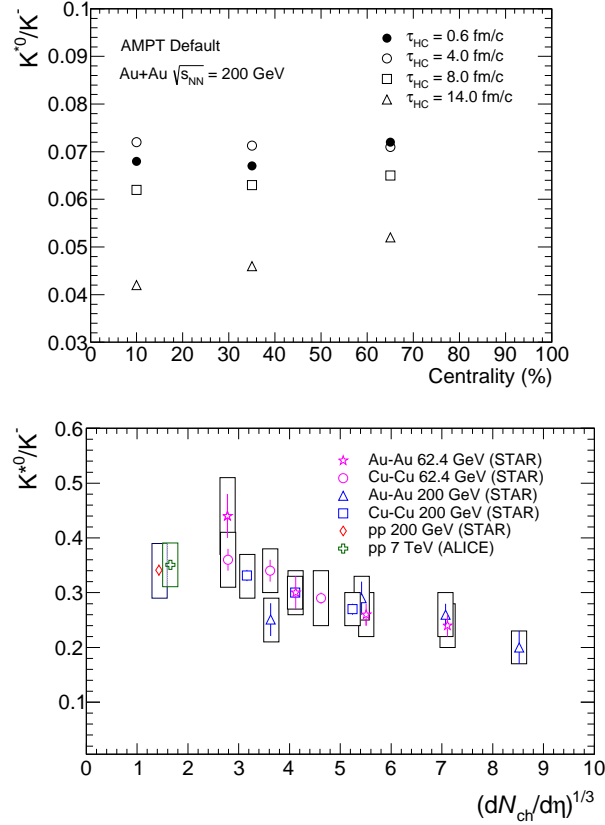
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Fig. 4. (Color online) Upper panel: K^{*0}/K^- versus collision centrality in AMPT model for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Results are shown for different hadron cascade time. Lower panel: K^{*0}/K^- as a function of $(dN_{ch}/d\eta)^{1/3}$ from experimental data in heavy-ion and p+p collisions.¹⁻⁵ The boxes represent systematic errors and vertical lines represent the statistical errors.

3.2. Observables for re-scattering effect

In this sub-section we discuss how to quantify the re-scattering effect in heavy-ion collisions. Figure 3 shows the dN/dy (upper panel) and mean transverse momentum ($\langle p_T \rangle$) of the reconstructed K^* as a function of hadron cascade time. As expected the dN/dy decreases due to re-scattering effects as hadron cascade time increases. We find the $\langle p_T \rangle$ values to increase as a function of hadron cascade time, this is also consistent with the loss of K^* due to re-scattering. This could also mark the increase of transverse flow with time.

However in order to provide a proper observable in an experiment for re-scattering we need an appropriate baseline to compare. One such observable could be the ratio of yield of K^* to K^- (K^*/K^-). Figure 4 (upper panel) shows the

K^{*0}/K^- versus collision centrality for different hadron cascade time. One observes a clear decrease in the value of the ratio with increase in the hadron cascade time. Indicating that the ratio is sensitive to re-scattering effect. At large hadron cascade time, the ratio shows a decrease from peripheral collisions to central collisions. The central collisions are expected to live longer and provide a medium with higher possibility of re-scattering. Hence a clear centrality dependence of K^*/K^- or a decrease in the value of K^*/K^- with respect to $p+p$ collisions would indicate dominance of re-scattering effect in heavy-ion collisions. Regeneration on the other hand would lead to increase of the ratio from peripheral to central collisions and with respect to $p+p$ collisions. Figure 4 (lower panel) shows the compilation of K^{*0}/K^- versus $(dN_{ch}/d\eta)^{1/3}$ experimental data from heavy-ion and $p+p$ collisions.¹⁻⁵ One observes that K^{*0}/K^- in $p+p$ collisions is larger than in central heavy-ion collisions. There is a clear centrality (reflected by the values of $(dN_{ch}/d\eta)^{1/3}$, where $dN_{ch}/d\eta$ is the number of charged particles per unit pseudo-rapidity) dependence of the ratio, thereby indicating presence of hadronic re-scattering in heavy-ion collisions.

4. Hadronic phase time

The suppression in K^*/K^- ratio in heavy-ion collisions with respect to $p+p$ collisions can be used to set a lower limit on the time difference between chemical and kinetic freeze-out. The experimental results shows that K^*/K^- decreases with increase in collision centrality. This implies that K^* re-scattering is dominant over K^* regeneration. This in turn means that $K^* \leftrightarrow K\pi$ is not in balance. Hence one can in principle use the K^*/K^- to get a lower limit estimate of the time between chemical and kinetic freeze-out as, $[K^*/K^-]_{kinetic} = [K^*/K^-]_{chemical} \times e^{-\Delta t/\tau}$. Where τ is the K^* life time, taken here as 4 fm/c ignoring any medium modification of the width of invariant mass distribution of K^* , supported by the experimental data.¹⁻⁵ Δt is the time between the chemical and kinetic freeze-outs. We assume that the $[K^*/K^-]_{chemical}$ is given by the experimental data in $p+p$ collisions and the heavy-ion collision data provides the $[K^*/K^-]_{kinetic}$. This is equivalent to assuming that all K^* which decay before kinetic freeze-out are lost due to re-scattering effect and there is no regeneration effect between kinetic and chemical freeze-out. AMPT model simulations (Fig. 2) shows this assumption could hold to a substantial extent. However these assumptions can only make the estimates of Δt to be a lower limit for the time difference between chemical and kinetic freeze-outs. Figure 5 upper panel shows the value of $[K^*/K^-]_{chemical}$ taken from the available experimental $p+p$ data to be 0.36 and the heavy-ion data (corresponding to $[K^*/K^-]_{kinetic}$) is taken from Fig. 4. The results for Δt boosted by the Lorentz factor ($\sim 1.38-1.57$) for three different centralities for various systems are plotted in the lower panel of Fig. 5. We find the time difference between chemical and kinetic freeze-out increases with both beam energy and system size as expected. For the central most Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, the lower limit of time between chemical and kinetic freeze-out is about 3.7 fm/c.

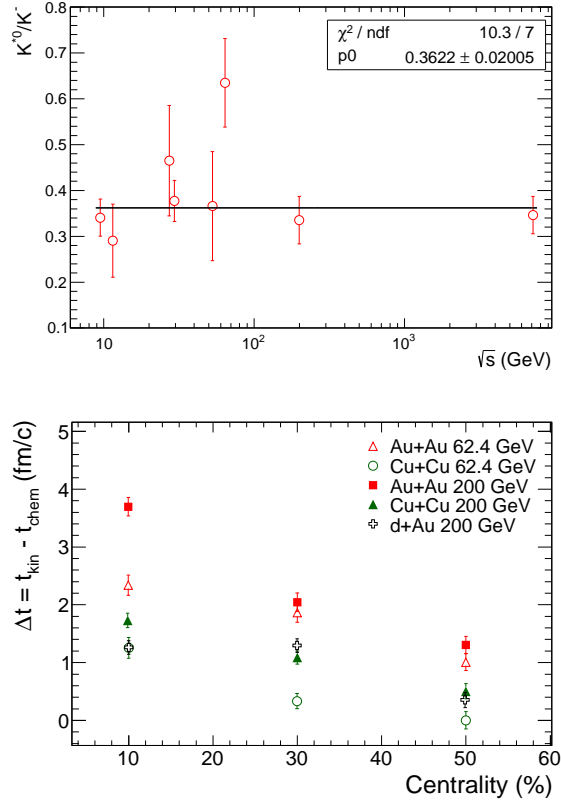
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Fig. 5. (Color online) Upper panel: K^{*0}/K^- for $p+p$ collisions at various center of mass energies. Lower panel: Estimate of the time difference between chemical and kinetic freeze-out for various collision systems and beam energies as a function of collision centrality. See text for details.

5. Summary

In summary, we have provided a detail study of effect of hadronic re-scattering on K^* production using the AMPT model. The study has been carried out by varying the termination time of the hadronic cascade. Larger the hadronic cascade time more is the re-scattering of the daughters (πK) of the K^* meson. We observe that the reconstructed K^* signal is lost due to re-scattering of the daughters which results in the change in their momentum distributions. There is a clear decrease in dN/dy of the reconstructed K^* meson with increase in hadron cascade time and the $\langle p_T \rangle$ increases with hadron cascade time. We propose an observable K^*/K^- as a function of collision centrality to study the re-scattering effect in heavy-ion collisions. A clear decrease in the K^*/K^- ratio with respect to $p+p$ collisions and with increase in collision centrality can be considered as a signature of re-scattering

effect in heavy-ion collisions. Within the framework of a toy model, it was possible to use the measured K^*/K^- ratio in $p+p$ and A+A collisions to estimate the lower limit of the time difference between chemical and kinetic freeze-out. For the most central collisions at RHIC this lower limit of the time difference is found to be about 3.7 fm/c, a value which is consistent with other estimates.^{22,23}

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